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Design of a leaky-wave long slot antenna using ridge waveguide

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Abstract: A new design of the leaky-wave long slot waveguide antenna with low cross-polarisation is proposed. The proposed antenna consists of a straight long slot located at the centre of the broad wall of the ridge waveguide. By properly designing the ridge, the amount of leakage power along the slot is controlled, which results in the desired aperture distribution. The aperture has a Taylor distribution with a sidelobe level of −35 dB. Such a design has a low cross-polarisation level as well as a desired beam pointing angle, which is defined at the beginning of the design procedure. The simulation results confirm the high accuracy of the design procedure. The proposed antenna is also fabricated and measured. According to the measurement results, the structure has a cross-polarisation of −41.9 dB and a sidelobe level of −26.3 dB. The measured reflection coefficient of the proposed antenna is −22.8 dB at the design frequency.

1 Introduction

Leaky-wave antennas have received a lot of attention in recent decades because of their interesting properties. These properties, such as capability of frequency scan, very high directivity and high efficiency, are stemmed from the non-resonance nature of this type of antennas. Also, the simple structure of this type of antennas makes it suitable for microwave and millimetre frequency bands applications, because it does not require a complicated feed network compared to its planar array type. This category of antennas is sometimes referred to as fast wave antennas. Examples of such antennas are presented in [1, 2]. Among all kinds of leaky-wave antennas, the long type, with a length of more than three times of the wavelength, has been widely investigated [3–15], and has been used in aerospace applications for many years [13]. The straight, long slot antenna is in fact the most basic type of the leaky-wave long slot antenna. This slot has a distance from the central axis of the broad wall of the waveguide which determines its amount of leakage. The propagation constant of this type of antennas has been investigated in [6–9]. Although this structure has the advantage of simple design and implementation, it has a drawback, that is, high sidelobe level (SLL). To eliminate this imperfection and obtain a proper radiation pattern, the aperture distribution must be properly tapered. A desired aperture distribution can be achieved through controlling the amount of leakage along the waveguide [10–18].

Balanis and co-worker have carried out the analyses on different kinds of long slots placed on an infinite ground plane [13]. As presented in this paper, the cross-polarisation level in a straight long slot is considerably lower than that of a meandered slot, with equal lengths. Also, if the slot on the waveguide is designed symmetrically, an improved cross-polarisation can be obtained compared to the similar asymmetrical one. However, a proper radiation pattern with low SLL is achieved using an asymmetrical slot. As illustrated in [19], locating the slot at the centre of the broad wall of the waveguide yields low level of cross-polarisation. In this paper, ridge waveguide is used to obtain the desired aperture distribution with low cross-polarisation. The slot is placed at the centre of the broad wall of the waveguide, and excited properly through a particular design of the periodic ridge. Consequently, an aperture distribution with a low SLL and cross-polarisation is obtained. It has to be mentioned that the shape of the ridge is determined, considering the desired beam pointing angle and the desired aperture distribution. This process will be elaborated in this paper. On the other hand, it is proved that using a ridge inside the waveguides causes a reduction in the waveguide dimensions [20–22]. The proposed design has resulted in a 20% decrease in the antenna dimensions compared to the conventional leaky-wave waveguide antennas.

2 Leaky-wave mode analysis

In a leaky-wave antenna, wave attenuation due to power leakage occurs simultaneously with wave propagation along the structure. A periodic configuration of a leaky-wave waveguide antenna is formed by periodically modulating the waveguide in some fashion. The fundamental mode of the periodic leaky-wave antenna is slow and thus non-radiating wave is formed. However, owing to the periodic nature of this type of leaky-wave antenna, a set of floquet modes was excited. The phase constant of the *n*th floquet mode, β_n, is determined as below [2]

$$\beta_n = \beta_0 + \frac{n\pi}{C} \quad (1)$$

wherein C is the half period and β_0 is the phase constant of the fundamental floquet mode, which is approximately equal to the phase constant of the closed waveguide. Through proper design of the structure, one of the floquet harmonic (usually $n = -1$) is a fast wave and then leakage will occur [2]. When the value of leakage constant, α, is negligible, the beam pointing angle is defined as below [2]

$$\sin\theta_m \cong \frac{\beta_{-1}}{k_0} \quad (2)$$

wherein θ_m is the beam pointing angle relative to the antenna broadside and k_0 is the free-space wave number. As shown in (2), the direction of radiation in a certain frequency is a function of the waveguide dimensions. The beam width, in order to obtain 90% efficiency, is determined as below [2]

$$\Delta\theta \cong \frac{1}{(\mathcal{L}/\lambda_0)\cos(\theta_m)} \simeq \frac{(\alpha/k_0)}{0.18\cos(\theta_m)} \quad (3)$$

wherein L is the antenna length. When the geometry of the leaky waveguide does not change in longitudinal direction, the leakage rate is constant along the waveguide and the aperture distribution has an exponential amplitude variation [3]. Such a distribution has a radiation pattern with a high SLL. To obtain the desired aperture distribution, the leakage constant must be controlled along the aperture. For a straight long slot antenna, controlling the leakage rate is feasible through tapering the distance between the slot and the waveguide's central line. Such a design has a radiation pattern with high level of cross-polarisation [13]. The level of cross-polarisation can be improved by placing the slot on the waveguide's centreline [19]. By properly exciting the slot, a superior radiation pattern with low cross-polarisation level is achieved. This is illustrated in detail in the following section.

3 Design principles for the proposed leaky-wave antenna

The proposed leaky-wave antenna consists of a straight long slot located at the centre of the broad wall of the ridge waveguide. The main idea of this design is to divide the straight long slot into segments with certain length and then exciting each segment by its corresponding ridge. Each segment of the slot will have its own leakage. To control the power leakage, proper design of the ridge is of vital importance. This design causes the ridge to be periodic, so a set of floquet modes were excited as discussed in the previous section. Owing to the use of the ridge inside the waveguide, the phase constant of the dominant TE_{10} mode is greater than the free-space wave number and thus, the fundamental floquet mode is a slow wave. However, a proper value of the segment length, C, makes the $n = -1$ floquet harmonic a fast wave at working frequency. On the other hand, the segment length affects the beam pointing angle, θ_m, according to (1) and (2). So, this parameter must be determined considering the desired beam pointing angle. The design procedure is explained in the following subsections. The design frequency for the proposed leaky-wave antenna is 10 GHz. It should be noted that simulations of the leaky-wave antenna were done by the well-known package ANSOFT HFSS.

3.1 Determination of the beam pointing angle and acquiring the leakage curve

Fig. 1 shows the proposed structure. As shown, the long slot is divided into N segments. Each segment is excited by its corresponding ridge, which has the distance $d_i (i = 1, 2, 3, \ldots, N)$ from the centre of the slot. In fact any increment in the value of d_i causes a disruption in the current distribution on the waveguide's broad wall, which results in the power leakage. As mentioned before, the length of the ridges in the segments determines the beam pointing angle of the leaky-wave antenna. So, to achieve the desired beam pointing angle, the value of C must be determined first. Knowing the value of C and the overall slot length, the number of segments, N, can be obtained.

To obtain the relationship between the segment length and the beam pointing angle, a variety of leaky-wave antennas with $d_i = 1$ mm is simulated in which the segment length is varied at every 0.01 mm from 10 mm to 14 mm. By the study of simulated radiation patterns for each leaky-wave antenna, the relationship between the segment length and the beam pointing angle can be achieved. This is shown in Fig. 2. It can be seen that the antenna beam pointing angle varies from −36.6° to −7.7° as the parameter C varies from 10 mm to 14 mm. At the design frequency of 10 GHz, for all values of this parameter, the $n = -1$ floquet harmonic is the only radiating mode. Therefore, Fig. 2 can be used to determine the value of C for the desired beam pointing angle.

To obtain the leakage constant, different methods such as measurement methods [4], analytical methods [6, 7] and numerical methods [8] have been used. To calculate this parameter, we used the full-wave HFSS software. As mentioned previously, the value of d_i determines the leakage constant. To calculate the relationship between the leakage constant and the distance, d_i, a family of leaky-wave antennas with different values of d_i is modelled according to Fig. 1. The values of d_i are varied at every 0.01 mm from 0 to 4 mm. The leakage constant can be obtained through the following equation

$$|S_{11}|^2 + |S_{21}|^2 = e^{-2\alpha L} \quad (4)$$

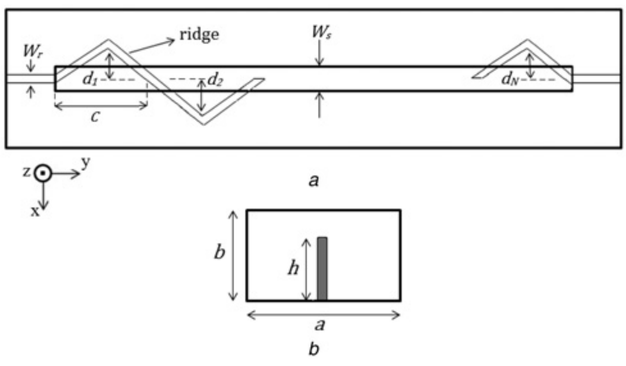

Fig. 1 *Proposed leaky-wave antenna for calculating the radiation characteristics*

a Top view
b Cross section at $y = 0$

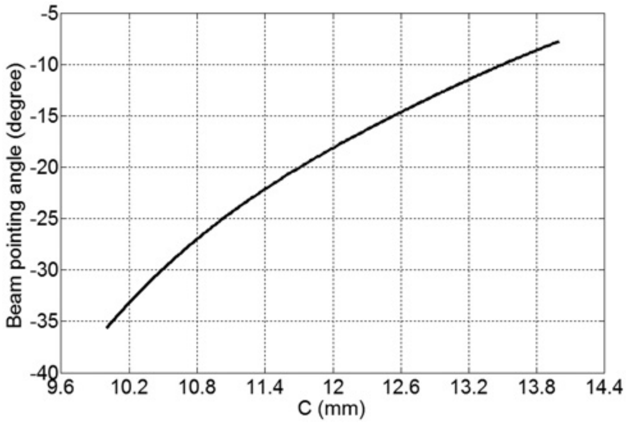

Fig. 2 *Beam pointing angle against segment length, C*

Fig. 3 shows the relationship between the leakage constant and d_i for three different slot widths. As shown in this figure, for $d_i = 0$, the leakage value is approximately zero. By increasing d_i, the leakage constant increases as well. On the other hand, the width of the slot affects the value of α, that is, the wider the slot, the higher the leakage constant. For example, for $d_i = 3$ mm and $w_s = 1.5$ mm the leakage value equals 0.047 dB/mm, whereas this value is 0.092 dB/mm for $w_s = 4.4$ mm. It has to be taken into account that wider slots result in a higher leakage at the beginning of the slot. Therefore to achieve the desired aperture distribution, controlling the leakage rate along the structure will be more difficult. As a result, the value of this parameter should be selected properly.

Another point to be noted is that variation in d_i causes a small distortion on the desired beam pointing angle. This aberration is due to the variation in the phase constant, β_{-1}. Considering Fig. 1 and by using (2), the relation between the phase constant and d_i can be obtained based on the previous procedure for determining the beam pointing angle. This relationship is plotted in Fig. 3 for $C = 11.4$ mm. According to the simulations, the value of w_s has no significant effect on the phase constant, so the curve is plotted for $w_s = 2.2$ mm. From this figure, β_{-1}/k_0 varies about 0.04 as the value of d_i varies from 0 to 4 mm.

3.2 Acquiring the ridge profile

In this subsection the leakage constant, $\alpha(y)$, along the slot is calculated using the well-known leaky-wave antenna equation. Then, the obtained results in the previous subsection will be used to calculate d_i. When the aperture distribution is known, the leakage constant value along the slot can be calculated as follows [2]

$$\alpha(y) = \frac{0.5|A(y)|^2}{(1/\eta)\int_0^{L} |A(y)|^2 \mathrm{d}y - \int_0^{y} |A(y)|^2 \mathrm{d}y} \tag{5}$$

wherein y is the antenna longitudinal axis, η is the efficiency of the leaky-wave antenna and is defined as the ratio of the radiated power to the injected power. The antenna efficiency is usually selected in the range of 90–95% [2]. In (5), the aperture distribution, $A(y)$, is a Taylor distribution with -35 dB SLL. When the slot length, L, is known, $\alpha(y)$ can be obtained from (5) and then the value of each d_i can be determined based on Fig. 3.

4 Simulation and measurement results

In this section, we will focus on the design of the leaky-wave antenna based on the presented principles in the previous section. As mentioned before, the desired beam pointing angle must be defined at the beginning of the design procedure. Here, the desired beam pointing angle is assumed to be 22°, therefore $C = 11.4$ mm considering Fig. 2. The slot width is set to 2.2 mm. For an antenna efficiency of 90%, $L = 313.5$ mm. This value divides the long slot into 28 segments ($N = 28$). Other dimensions are set as follows: $a = 18$, $b = 9$, $W_r = 1.92$ and $h = 8.2$ mm. Taylor distribution with -35 dB SLL is shown in Fig. 4. Now, the leakage rate along the slot can be obtained according to (5). This parameter is shown in Fig 5. To know the amount of leakage for each segment of the slot, $\alpha(y)$ curve in Fig. 5 is sampled with a sampling interval of 11.4 mm. This value is in fact the distance between adjacent segments centre. As mentioned before, there are 28 segments whose corresponding leakage values are shown in Fig. 5. Based on Fig. 3, the value of each d_i can be obtained, which is shown in Fig. 6. The fabricated leaky-wave antenna is shown in Fig. 7. In Fig. 8, the measured and simulated reflection coefficients of the designed leaky-wave antenna are shown. From this figure, the measured reflection coefficient has a value of -22.8 dB at the design frequency of 10 GHz. It should be noted that the difference between the simulation and measurement results is due to the fabrication procedure. The simulated and measured H-plane patterns of the proposed antenna at

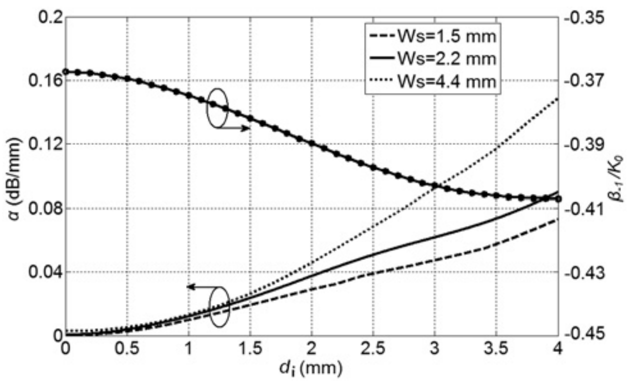

Fig. 3 *Relation between leakage constant and phase constant with d_i*

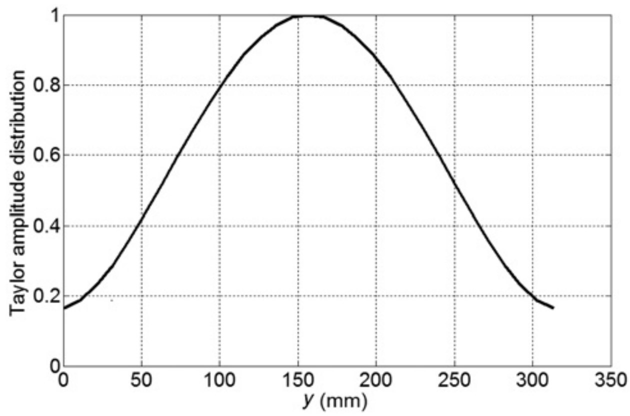

Fig. 4 *Taylor aperture distribution with − 35 dB SLL*

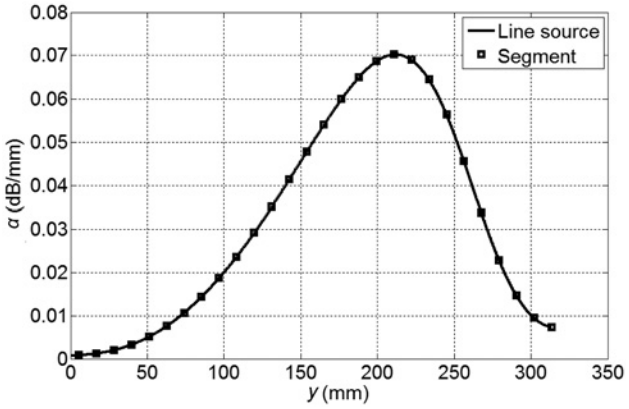

Fig. 5 *Leakage constant along the slot*

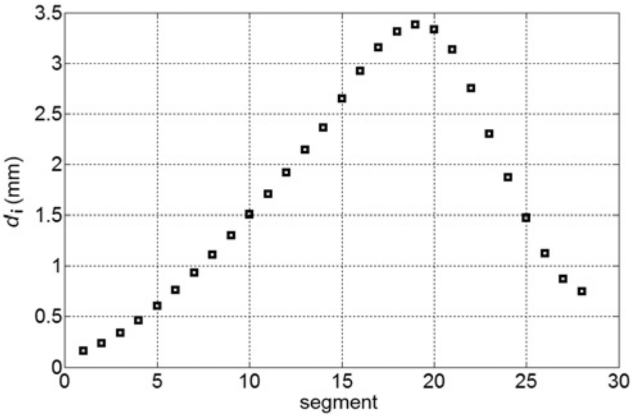

Fig. 6 *Values of d_i for each segment*

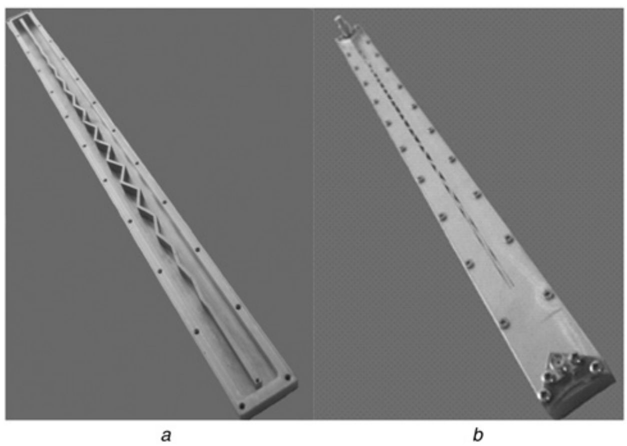

Fig. 7 *Fabricated antenna*

a Internal view
b External view

10 GHz frequency are shown in Fig. 9. As depicted in this figure, the beam pointing angle is −23.4°, which has only a 1.4° difference with the desired beam pointing angle which suppose at the beginning of the design procedure. This small difference is due to the variation in the phase constant along the slot. Considering Fig. 3 for values of d_i from 0 to the maximum shown in Fig. 6 (i.e. 3.38 mm), it can be found that β_{-1}/k_0 varies about 0.038 along the structure. The corresponding beam pointing angle, shown in Fig. 10,

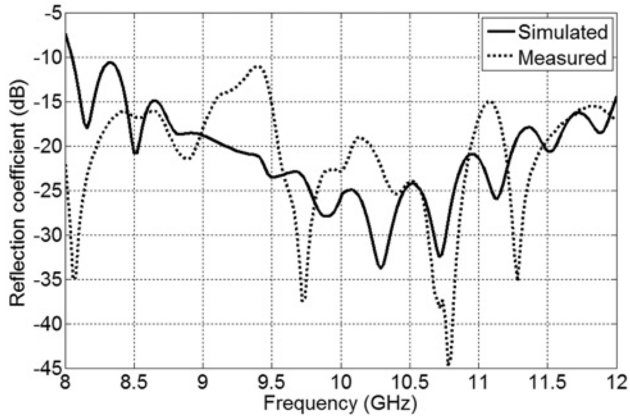

Fig. 8 *Measured and simulated reflection coefficients*

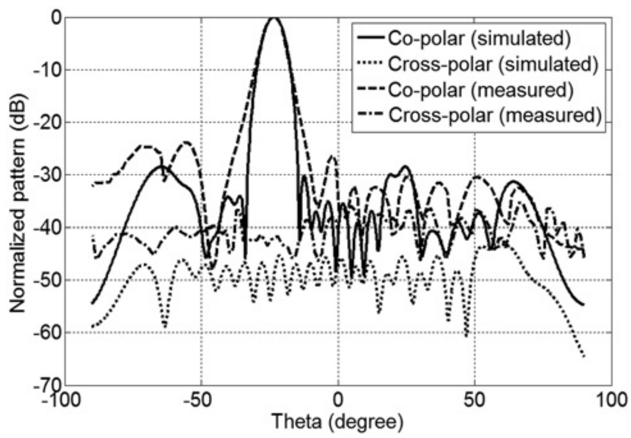

Fig. 9 *Simulated and measured H-plane patterns at the design frequency*

indicates that the beam pointing angle varies about 2.5° along the slot. It should be noted that in order to keep the beam pointing angle at the desired value and prevent the main beam from broadening, two geometrical parameters must be simultaneously tapered [11, 15, 16, 18] and in this design a more accurate result can be obtained by modulating at the same time d_i and each segment length, C_i. But, because the radiation pattern of the proposed leaky-wave antenna (Fig. 9) with typical gain of 16.5 dBi does not get distorted significantly, we focused to modulate only one physical parameter, d_i.

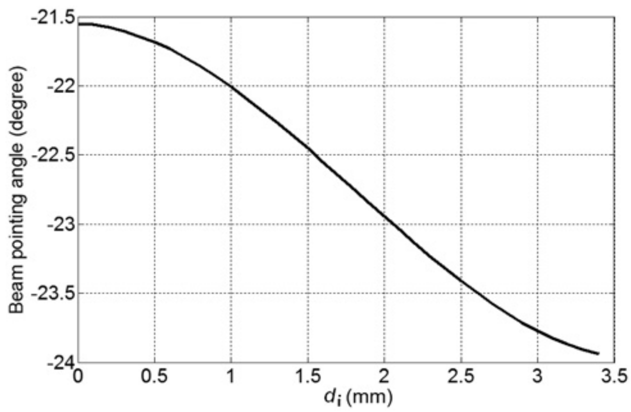

Fig. 10 *Variation of beam pointing angle along the slot*

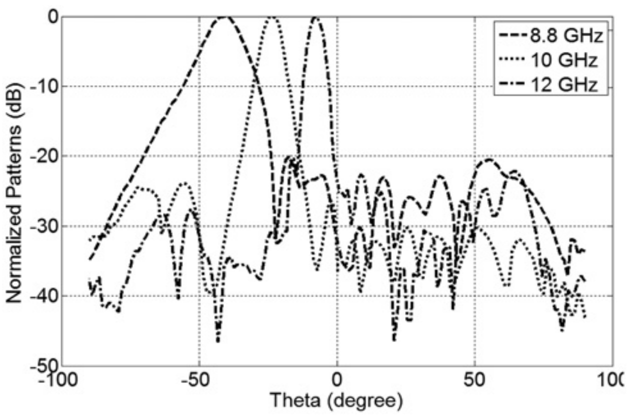

Fig. 11 *Measured and simulated H-plane patterns of the leaky-wave antenna at different frequencies*

Table 1 Radiation characteristics of the proposed leaky-wave antenna at different frequencies

Frequency, GHz	Beam width	Gain, dBi	SLL, dB	Beam direction
8.8	12.6	14.1	−20.1	−39.8
10	6.9	16.5	−26.3	−23.4
12	5.4	16.2	−21.5	−7.4

As shown in Fig. 8, the simulated SLL is −30 dB, while the measured one is −26.3 dB. As mentioned before, this difference is due to the fabrication process. From the measurement results, the radiation efficiency of the leaky-wave antenna is 88% at 10 GHz. As previously mentioned, low cross-polarisation is one of the advantages of using the ridge in the proposed structure. From Fig. 9, the measured cross-polarisation is −41.9 dB.

To investigate the beam scan behaviour in the proposed antenna, the antenna pattern has been measured at 8.8 GHz as well as at 12 GHz frequencies. The results are shown in Fig. 11. It can be seen that in the frequency range of 8.8–12 GHz, the beam direction scans from −39.8° to −7.4°. By increasing the frequency, the beam direction moves towards the antenna broad side. The antenna does not show a good performance outside this frequency range. All the radiation characteristics of the proposed antenna are presented in Table 1. Also, it has to be mentioned that due to using the ridge inside the waveguide, the dimensions of the antenna have reduced by 20% compared to conventional leaky-wave antennas.

5 Conclusion

In this paper, a new design of the leaky-wave long slot antenna is presented. Ridge waveguide is used in the proposed design, which considerably decreases the cross-polarisation level. Through proper design of the periodic ridge, the long slot located at the centre of the broad wall of the waveguide is suitably excited, and finally, the desired aperture distribution is achieved. The simulation results confirm the highly accurate design procedure. The proposed leaky-wave antenna was fabricated, and the measurement results at the design frequency show that the H-plane cross-polarisation and SLL are −41.9 and −26.3 dB, respectively. The frequency scan property of the leaky-wave antenna was also investigated, and it was found out that the antenna scans the −39.8° to −7.4° region in the 8.8–12 GHz frequency range. The reflection coefficient of the proposed antenna was also measured and the results are acceptable within the operational frequency range of the antenna. Using the ridge waveguide resulted in a 20% decrease in the dimensions compared to the conventional leaky-wave waveguide antennas.

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